THE RELATIONSHIP OF THE ENERGY INPUTS TO THE NET ENERGY PRODUCTION OF FULLY INTEGRATED ENERGY-PRODUCING SYSTEMS

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INTRODUCTION

The net energetics and the energy inputs into integrated,synthetic energy-producing systems are extremely important to the development of new energy supplies. Basically, the ultimate goal is to design and operate environmentally acceptable systems to produce new supplies of salable energy, whether they be low-Btu gas, substitute natural gas (SNG), synthetic crude oil, methanol, ethanol, hydrogen, or electric power from primary raw materials such as coal, oil shale, biomass, organic wastes, and isotopes, at the lowest possible cost and with the minimum consumption of energy inputs.

It is essential to quantify how much energy is expended and how much salable energy is produced in *each fully integrated system*. An energy budget should be prepared because the capital, operating, and salable energy cost projections, and the conversion process efficiency are insufficient alone to choose the best systems. These figures do not necessarily correlate with net energy production (1,2). Also, the "capital energy investment" consumed during construction of the system should be recovered during its operation. Comparative analyses of similar systems for the production of synthetic liquid and gaseous fuels from the same feedstock or of different systems that yield the same fuels from different raw materials should be performed by consideration of the economics *and* the net energetics. This approach to the selection of optimum systems is not limited to the production of substitute fossil fuels; synthetic energy systems per se such as nuclear power systems can also be treated in the same manner.

Recently, several reports have been published on the analysis of the net energetics of different systems, but there is by no means general agreement as to the conclusions of these studies. For example, for nuclear systems, Chapman states that if capacity grows too fast, the system will consume more energy than it produces (3), while Wright and Syrett state that the case for building nuclear power stations to conserve precious fossil fuel is overwhelmingly clear (4). Hoffman concluded that when all energy inputs are considered, such as mining uranium iron ore, enriching nuclear fuel, and fabricating and operating power plants and reprocessing facilities, the net electrical yield is very low (5). Yet, Davis stated that all the energy invested in a nuclear power plant during construction is repaid after only 2.3 months of full power operation (6).

Synfuel systems are not immune to these apparent contradictions either. For shale oil recovery, the net energy recovery (energy out/energy consumed) is reported to range from a ratio of 10 (Arco) to an energy standoff (Texaco), while the U.S. Federal Energy Administration wonders whether a mammoth shale oil operation would consume more energy than it yields (7,8). In contrast, coal gasification is stated to have a recovery ratio, at least for one system, of 5 (7). Conversion of biomass and wastes to synfuels appears to be characterized by relatively high energy recovery ratios (1,2,9).

An important factor that is often ignored in energy input-output analyses is that it is not essential for the energy consumed in the system to be less than the energy produced in the form of salable energy products. This depends on the quality of synfuel and the quality of the primary energy source as well as the quality of the external non-primary energy source inputs. Thus, oil shale cannot be utilized in the same manner as heating oil, which clearly has a higher intrinsic value than oil shale. So a synfuel production system that consumes more energy than it produces as salable synfuels may be acceptable and in fact necessary in some cases.

The analysis of net energetics can be performed using many different methods and a myriad of symbols and definitions. For example, some energy analysts feel that only an analysis based on the Second Law can provide the ultimate answers in terms of where more available energy, in the thermodynamic sense, can be found to permit true efficiency maximization.* Others believe that the conventional energy balance is optimal because it is more realistic and easier to use. Indeed, for integrated synfuel production systems, entropic losses may not always be definable for all segments of the system, and a rigorous Second-Law analysis cannot be performed. In the final analysis, it seems reasonable to assume that an integrated synfuel-production system is an isolated one into which primary and nonprimary energy inputs, suitably normalized with respect to quality, are injected, and salable energy products are withdrawn. After all, the energy products utilizable by the consumer correspond to the actual "available" energy.

The location of the system boundaries is of paramount importance in the net energy analysis of integrated synfuel production systems (10). It is probably desirable to transform the primary energy source, all materials used in building the system components, and all external energy inputs needed to operate the system, into their original sources in the ground. For example, the steel used in system construction consumed energy on fabrication and installation, yet its energy precursors also include proportional energy increments from steel production, the energy required to mine the iron ore, and the energy needed to manufacture the materials of construction for the iron ore mines and steel plants. The definition of system boundaries must also consider the nonadditive nature of different energy inputs by integrating them back to the original energy source, such as gasoline from crude oil and electricity from coal. Yet, coal and crude oil are not identical and the energies consumed by the system in terms of original energy sources in the ground are not strictly additive. The energy products of commercial systems will also not be single fuels, but will consist of several synfuels and salable by-products.

Obviously, the details of the system design and its boundaries, operating conditions, and constraints affect the net energetics, so it is difficult to compare the conclusions of different studies, especially when the ground rules are not the same (11). An analytical methodology derived independently of the type of synthetic energy system would be very useful if valid predictions could be made by application of the method to integrated systems. The purpose of this paper, therefore, is to present a simple theoretical approach to net energetics based upon principles rather than actual system examples. This analysis emphasizes the quantitative relationship of the external energy inputs to the net energetics of an energy-producing system. It is believed that the use of this concept *in conjunction with economic projections* will facilitate the comparative analysis of a broad range of systems and permit the selection of those systems that can add the largest amount of salable new energy to our economy.

DERIVATION OF RELATIONSHIP

A totally integrated synfuel or synthetic energy system is composed of many different unit operations. For example, a coal gasification system for the production of SNG consists of coal mining, transportation of coal to the gasification plant site, conversion of the coal to SNG and other products, disposal of unwanted residuals, transport of the gasification plant products to transmission lines and product distribution points, transport of these products to storage and the end-product users, and recycling of certain product streams such as water to particular unit operations. Air, water, and land pollution control and the acquisition of raw materials other than the primary energy source (coal) are some of the supporting activities in a hypothetical system for producing salable SNG.

All of these unit operations require energy in one or more forms.

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* A generalized definition for the Second-Law efficiency is the ratio of the least available work required to the actual available work used and includes entropy changes.

For a totally integrated synthetic energy-producing system composed of many different unit operations in the steady state, the overall efficiency for salable energy production is given by:

$$\frac{E_P}{E_F + E_X} = f_{sy} \tag{1}$$

Where, per unit of primary energy source:

E_P = Energy content of salable energy products

E_F = Energy content of primary energy source

E_X = Sum of energy contents of all energy inputs except primary energy source

f_{sy} = Energy production efficiency.

E_X includes the nonprimary energy inputs and, depending on the system boundaries, the capital energy investment in system construction possibly amortized over the life of the system or specific system units, and the energy consumed in producing the materials introduced into the operating system.

Similarly, the energy production efficiency for the same integrated system is given by:

$$f_1 \cdot f_2 \cdot f_3 \cdots f_n = f_{sy}$$

where:

$f_1 \cdots f_n$ = The energy efficiency of each unit operation in the integrated system.*

Lumping all unit operations except one together gives:

$$f_o f_p = f_{sy} \tag{2}$$

where:

f_o = The product of the energy efficiencies of all unit operations except one

f_p = The energy efficiency of one unit operation such as the process for converting the primary energy source to synfuel

Equating (1) and (2) and rearranging gives:

$$\frac{E_P}{f_p(E_F + E_X)} = f_o \tag{3}$$

Now, let the net energy production ratio (N) for the integrated system be given by:

$$\frac{E_P - (nE_F + mE_X)}{(nE_F + mE_X)} = N \tag{4}$$

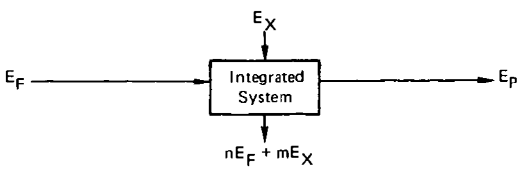
where:

n = Fraction of E_F diverted to other than salable energy products

m = Fraction of E_X diverted to other than salable energy products

$(nE_F + mE_X)$ = Total energy consumed by integrated system

This model assumes that the energy "consumed" within the integrated system consists of energy losses and the energy diverted to other than salable energy products. The model also assumes that E_P is derived from E_F or both E_F and E_X. Diagrammatically, the system can be represented by:



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* For those systems that contain parallel unit operations, each parallel block is one unit operation.

The input-output balance is:

$$E_F + E_X = E_P + nE_F + mE_X$$

The coefficient, m, is 1.0 in many systems that consist of individual unit operations where none of E_X contributes to E_P, such as in gas transmission and coal mining. In other systems, m can be less than 1.0 because some of the unit operations derive a portion of E_P from E_X. For example, E_X might be used to generate hydrogen from water for use within the system to convert the primary energy source to energy products.

If all the energy consumed is of the nonprimary type, i.e., n is zero, the total system is replacing exactly the amount of external nonprimary energy source inputs consumed as salable synfuel when N is zero. When N is greater than zero, the total system is producing an amount of energy as salable synfuel equal to the sum of the external nonprimary energy source inputs consumed by the system plus an additional increment as salable synfuel. Where part of the energy content of the primary energy source is used within the integrated system, this energy input (nE_F) is added to mE_X to compute N by equation (4). The variation of E_P and N with the type of energy consumed is summarized in Table 1.

Table 1. VARIATION OF E_P AND N WITH TYPE OF ENERGY CONSUMED BY INTEGRATED SYSTEM

	Salable Energy Products, E_P		
Energy Consumed	$N = 0$	$N < 0$	$N > 0$
All non-primary	$E_P = mE_X$	$E_P < mE_X$	$E_P > mE_X$
All primary	$E_P = nE_F$	$E_P < nE_F$	$E_P > nE_F$
Non-primary and primary	$E_P = (nE_F + mE_X)$	$E_P < (nE_F + mE_X)$	$E_P > (nE_F + mE_X)$

Rearranging (4) to solve for E_P and substituting for E_P in (3) provides:

$$\frac{(nE_F + mE_X)\ (N + 1)}{f_p(E_F + E_X)} = f_o \qquad 5)$$

For given values of N, f_p and f_o, the total energy consumed by the integrated system is the same whether this input is made up of nE_F only, mE_X only, or both. So for various assumed values of N, f_p, and f_o, the total energy consumed ($nE_F + mE_X$) can be calculated as a function of E_F and expressed as a percentage of the energy content of the primary energy source (percentage factor x E_F). This can be achieved for example by assuming that nE_F is zero and then solving for mE_X.

$$mE_X = \left(\frac{f_of_p}{N + 1 - f_of_p}\right) E_F \qquad 6)$$

where:

$\dfrac{f_of_p}{N + 1 - f_of_p}$ = Fraction of primary energy source energy equivalent utilized within system

Thus, Figure 1 shows a family of curves for N equal 0 to 20 and f_p equal 75% in which f_o is plotted against this percentage factor. Figure 2 is a plot of the energy production efficiency of the fully integrated system (f_{sy}) against this factor and was constructed in a similar manner. Several variations of the plot format are of course possible, such as changing the units of the ordinate to consumed energy units by using a specified primary energy source.

DISCUSSION

The family of curves presented in each figure illustrates the quantitative relationship of the energy inputs consumed by the integrated system and the efficiencies of utilizing these inputs to the net energy production ratio of the integrated system. For a given system, the higher the net energy production ratio, the greater the efficiency of converting the energy inputs to salable energy products. However, it can be seen from the curves in Figure 2 that a synfuel production system can be operated at a higher overall efficiency for salable energy production (f_{sy}) than a similar system, but still have a lower net energy production ratio (1). The curves can thus aid in the comparative analysis of several systems.

The curves can also be used for predictive purposes to assist in the optimization of a new system. For example, calculation of f_p from the synfuel conversion process characteristics and construction of the appropriate set of curves similar to those in Figure 1 permits the energy consumed ($nE_F + mE_X$) to be related quantitatively to f_o and N. In an actual integrated system, tabulation of ($nE_F + mE_X$) from the energy budget would permit the range of possible N's to be determined as a function of f_o. Depending on the actual values of the parameters, it might be concluded that a selected N value is not possible unless a finite improvement can be made in f_o. Modification of one or more unit operations to supply the necessary incremental increase in f_o could then be considered. Conversely, for a constant f_o, a Figure-1 type plot could be prepared for a range of f_p's of one unit operation, and its effect on the system N's and energy consumption could be considered in the same manner.

Several interesting conclusions can also be drawn from the figures regarding the characteristics of integrated energy-producing systems. It can be seen that ($nE_F + mE_X$) exhibits a series of maximum permitted values at the maximum f_o; i.e., when all of the unit operations except f_p are functioning at idealized efficiencies of 100%. A tabulation of the maximum energy inputs expressed as the product of a percentage factor and E_F can be compiled for different N's and f_p's as shown in Table 2.

Table 2. MAXIMUM VALUES OF TOTAL ENERGY INPUT

N	f_p, %	Factor*
1.0	100	1.000
1.0	75	0.600
1.0	50	0.333
2.0	100	0.500
2.0	75	0.333
2.0	50	0.200
3.0	100	0.333
3.0	75	0.231
3.0	50	0.143
5.0	100	0.200
5.0	75	0.143
5.0	50	0.091
10.0	100	0.100
10.0	75	0.073
10.0	50	0.048

*Maximum value of ($nE_F + mE_X$) is Factor x E_F.

For a given value of N, the maximum value of the energy consumed decreases more rapidly with f_p at low N values as compared to the corresponding decrease at high N values, but the maximum value permitted at the higher N's is quite small compared to the corresponding value at the low N's. Thus, for high net energy production, the maximum energy input into the integrated system is a relatively small fractional equivalent of the energy content of the primary energy source even at the high f_p's. This means that high f_o's are very desirable in the development of synthetic energy production systems. For values of N of about 10 or more, the maximum value of the energy consumption at idealized f_o's or f_{sy}'s of 100% is less than one-tenth of E_F in all cases. So in real systems where the f_o's and f_{sy}'s are less than 100%, the maximum energy consumption permitted to achieve high net energy production ratios will be considerably less than one-tenth of E_F. (However, as alluded to in the Introduction, it is not essential that all systems have high net energy production ratios because of the differences in quality of the energy inputs and products.)

Another observation that can be made from the figures is that at high N's, the rate of change of N with f_o or f_{sy} is small compared to the rate of change at smaller N's. The overall system efficiency will therefore have more effect on the absolute value of $(nE_F + mE_X)$ at the lower net energy production ratios.

SUMMARY

The basic concept proposed in this paper is believed to be broadly applicable and useful for the development of new synfuel supplies. The concept also suggests ground rules for the analysis of the net energetics of fully integrated systems. Support for the methodology is expected from its application to real systems.

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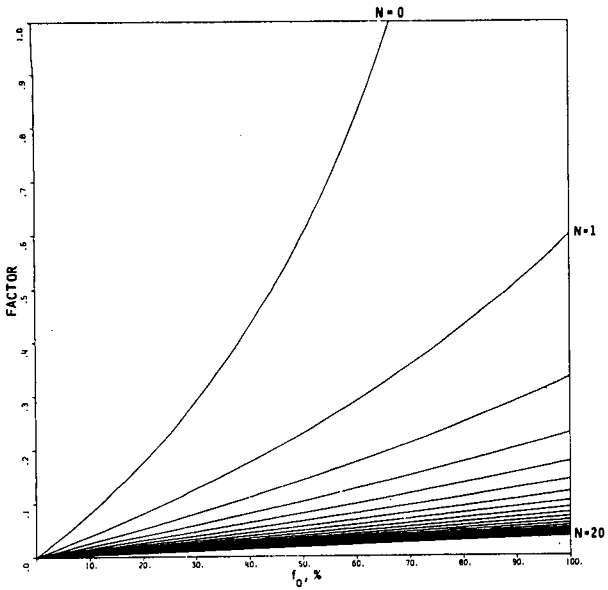

Figure 1. f_o vs. FACTOR FOR f_p OF 75.0%

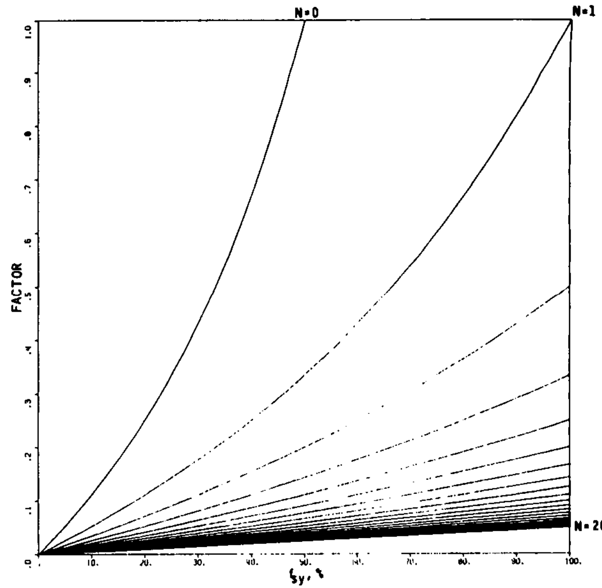

Figure 2. f_{sy} vs. FACTOR